CALCULATION OF GODIVA'S EFFECTIVE DELAYED NEUTRON FRACTION USING NEWLY-CALCULATED DELAYED-NEUTRON SPECTRA

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Abstract - When calculating the effective delayed neutron fraction, β_{eff}, for a given reactor system, the assumed delayed neutron group spectra and the assumed number of delayed neutrons born per fission, ν_d, can have a major impact on the final value. Over the years, the recommended values for the delayed neutron spectra and for ν_d have slowly changed. To ascertain whether or not these changes have increased the accuracy of β_{eff} calculations in fast ^{235}U systems, we have re-evaluated β_{eff} for the benchmark system Godiva-I using newly-calculated delayed-neutron spectra (Campbell and Spriggs, 1999) and Tuttle's recommended values of ν_d for both ^{235}U and ^{238}U (Tuttle, 1979).

THEORY

The effective delayed neutron fraction is defined as the adjoint- and spectrum-weighted delayed neutron production rate divided by the adjoint- and spectrum-weighted total neutron production rate. In its most general form (Keepin, 1965), β_{eff} can be calculated from,

$$\beta_{eff} = \frac{\sum_m \sum_i \int \psi \chi_{di}^m \beta_{oi}^m \nu_t^m \Sigma_f^m \Phi \, d\Omega \, d\boldsymbol{r} \, dE \, dE'}{\sum_m \int \psi \chi_t^m \nu_t^m \Sigma_f^m \Phi \, d\Omega \, d\boldsymbol{r} \, dE \, dE'} \quad , \tag{1}$$

where

Ω, E, and $\boldsymbol{r}$ represent angle, energy, and position, respectively,

m = the isotope,

i = the delayed neutron group,

$\Phi = \Phi(\boldsymbol{r}, \Omega, E)$ = the angular flux,

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$\psi = \psi(\boldsymbol{r}, \Omega, E)$ = the angular adjoint flux,
$\Sigma_f^m = \Sigma_f^m(\boldsymbol{r}, E')$ = the macroscopic fission cross section,
$\nu_t^m = \nu_t^m(E')$ = the average total number of neutrons released per fission, and
$\beta_{oi}^m = \beta_{oi}^m(E')$ = the delayed neutron fraction of the i^{th} delayed neutron group, defined as

$$\beta_{oi}^m = \frac{a_i \nu_d^m}{\nu_t^m} \quad , \tag{2}$$

where a_i is the relative abundance of the i^{th} delayed neutron group. The spectra contained in Eq. (1) are defined as follows: χ_{di}^m is the normalized delayed neutron spectrum for the i^{th} delayed neutron group, and χ_t^m is the normalized total neutron spectrum, which, for the m^{th} isotope, is defined as

$$\chi_t^m = \left(1 - \sum_i \beta_{oi}^m\right)\chi_p^m + \sum_i \beta_{oi}^m \chi_{di}^m \quad , \tag{3}$$

where χ_p^m is the normalized prompt neutron spectrum.

The effective delayed neutron fraction can also be written as,

$$\beta_{eff} = \gamma\beta_o \quad , \tag{4}$$

where $\bar{\gamma}$ is the average *effectiveness* factor and β_o is the fundamental delayed neutron fraction for the integral system. According to Keepin (1965), the effectiveness factor is the parameter that accounts for spectral differences between delayed and prompt neutrons. For reactor systems in which the fissioning isotopes are homogeneously mixed, β_o is the neutron-population-weighted delayed neutron fraction of the various isotopes.

RESULTS

To test whether delayed neutron data for the fast fissioning of ^{235}U and ^{238}U has changed significantly over the past 50 years, β_{eff} has been recalculated for the Godiva-I system using currently recommended delayed neutron spectra (Campbell and Spriggs, 1999) and ν_d and ν_t values for ^{235}U and ^{238}U. To perform this calculation, Godiva-I was modeled using the deterministic transport code, DANTSYS (Alcouffe), and the 16-group Hansen-Roach cross sections (Hansen, 1961).

Average Effectiveness Factor

The delayed neutron group spectra assumed for this study were obtained from the most current precursor spectral data contained in the ENDF/B-VI files for the fast fissioning of ^{235}U and ^{238}U. These data were combined by weighting the ^{235}U and ^{238}U spectra in accordance to their respective fissioning fractions occurring in Godiva to obtain an average spectrum for each delayed neutron group. For a near-critical configuration of Godiva, the average effectiveness factor calculated using Eq. (1) was $\bar{\gamma}=1.0573$.

In comparison, Keepin (1965) calculated $\bar{\gamma}$ = 1.034 using the spectral data of Batchelor (1956) and Bonner (1956), and $\bar{\gamma} \sim 1.0$ using the spectral data of Burgy (1946). Hansen (1962), on the other hand, calculated $\bar{\gamma}$ = 1.078, but did not reference the spectral data used to perform his calculation.

β_o *Calculation*

The fundamental delayed neutron fraction, β_o, for this study was obtained by summing the contribution of delayed neutrons from both the ^{235}U and the ^{238}U contained in the fuel and then dividing the sum by the average total number of neutrons released per fission. In accordance to the DANTSYS solution, 99.18% of the fissions occur in the ^{235}U and 0.82% in the ^{238}U, yielding an average value of $\bar{\nu}_t$ = 2.596. If we assume the delayed neutron yields recommended by Tuttle (1979) (see Table I), then $\beta_o = 0.00653 \pm 0.00014$. For a $\bar{\gamma}$=1.0573, this yields an effective delayed neutron fraction of 0.00690 ± 0.00015. This result is 4.7% higher than the value of $\beta_{eff} = 0.00659 \pm 0.0001$ experimentally measured by Hansen (1962) using the mass-increment method.

Table I. Comparison of β_{eff} Calculations

	Keepin	Hansen	This Work
Fission Fraction ^{235}U	.9911		.9918
Fission Fraction ^{238}U	.0089		.0082
$^{235}\nu_d$	.0165		.0167
$^{238}\nu_d$	.0412		.0439
$^{235}\nu_t$	2.57		2.594
$^{238}\nu_t$	2.79		2.783
β_o	.0064	.0064	.00653
$\bar{\gamma}$	1.034	1.078	1.0573
β_{eff}	.0066	.0069	.0069
C/E	1.002	1.047	1.047

In comparison, Keepin (1965) calculated a fission fraction of 99.11% for ^{235}U and 0.89% for ^{238}U. Using a value of $\bar{\nu}_d = 0.0165 \pm 0.0005$ for fast fission of ^{235}U and $\bar{\nu}_d = 0.0412 \pm 0.0017$ for fast fission of ^{238}U, Keepin calculated a $\beta_o = 0.0064 \pm 0.0002$. For a $\bar{\gamma}$=1.034 (from the Batchelor (1956) and Bonner (1956) spectra), this yielded an effective delayed neutron fraction of 0.0066 ± 0.0002, which agrees very well with the measured value. Similarly, Hansen (1962) assumed a β_o = 0.0064. But, when coupled with a $\bar{\gamma}$ = 1.078, arrived at a β_{eff} = 0.0069.

DISCUSSION

There is a 4.7% difference between the computed and measured values of β_{eff} for Godiva using current recommendations for the delayed neutron spectra and for the average number of neutrons born delayed.

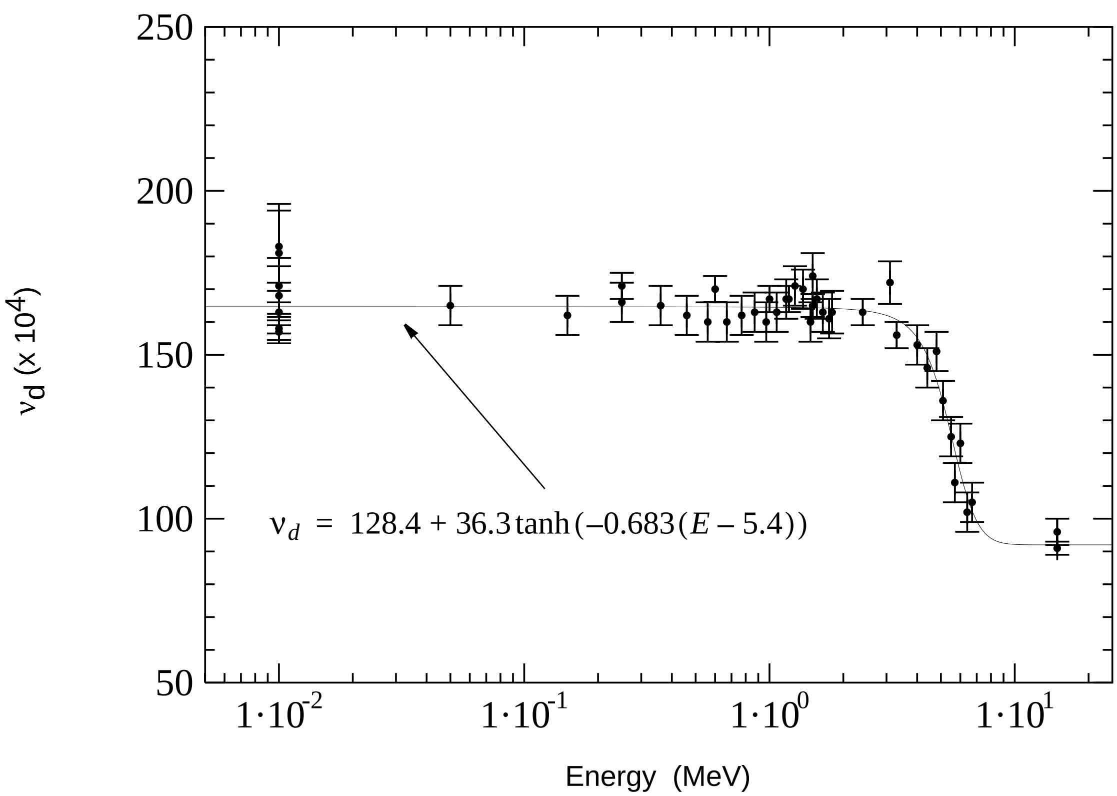

Fig. 1. Experimental values of delayed neutron yield per fission for ^{235}U. (Note, the seven data points plotted at 0.01 MeV actually correspond to data points taken at thermal energies, but have been plotted at 0.01 MeV on this figure so that the data from 0.1 to 14.9 MeV would not be excessively compressed.)

Part of this discrepancy is attributable to an increase in the effectiveness factor (i.e., 1.034 to 1.053) using the spectra contained in ENDF/B-VI, and part of it is attributable to an increase in β_o resulting from an increase in the recommended values of ν_d and ν_t for both ^{235}U and ^{238}U. However, the increase may not be justifiable. If all of the known experimental data for ν_d for the fissioning of ^{235}U is least-squares fit (see Fig.1), then ν_d appears to be 0.01644 rather than 0.01672 as recommended by Tuttle (1979). This would decrease the calculation of β_{eff} to 0.00679, which is only 3% higher than the measured value.

CONCLUSIONS

It would seem that the current recommended values of delayed neutron spectra and ν_d for fast fissioning of ^{235}U and ^{238}U do not increase the accuracy of β_{eff} calculations for fast systems. In fact, the evolution of the data seems to be decreasing the correlation between calculated and experimentally measured β_{eff}.

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